Inspiration from Nature toward the Design of Surface-roving Biomorphic Explorers

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Neuromechanical insights gained from studying sprawled, posture animals here on earth promises to inspire the design of mobile, biomorphic explorers. Arthropods, amphibians and reptiles offer an incredible array of design solutions. They differ in body size, leg number, leg arrangement and skeletal type. They locomote in a wide variety of habitats - from being inverted on the underside of leaves in a rainforest to running on ice. Fortunately, our recent discoveries on animal locomotion are consistent with the stated goals of biomorphic, legged mobility platforms. A surprising degree of performance appears to be preprogrammed in an animal's morphology. Control residing in the morphology permits simple feedforward control to be remarkably effective.

Remarkable general patterns of locomotor dynamics have emerged despite the unbelievable diversity. During low intensity terrestrial locomotion, a wide base of support and a low center of mass allows many-legged, sprawled posture animals to be highly statically stable. At faster speeds, we found that even these many-legged, sprawled postured animals use dynamic gaits. They can operate like inverted pendulums during walking and spring-mass systems during running. We have shown that many extraordinarily diverse morphological solutions appear to be adequate for running. Surprisingly, at fast speeds, despite differences in morphology, two-, four-, six- and eight-legged animals produce ground force patterns that are fundamentally similar. All are running or bouncing. The patterns of whole body ground reaction forces produced by the cockroach are similar to those produced by trotting eight-legged crabs, four-legged mammals and running bipeds. In each species, two sets of legs propel the body alternately - a set being one leg for a biped, two for a trotting quadruped, three for cockroaches and four for crabs. The movement of each of these species can be described by a mass atop a spring where the mass represents the body and the virtual leg spring characterizes the behavior of one to four legs.

In contrast to most birds and mammals where all legs work in a similar way during hopping, trotting and running, pairs of insect legs each work differently. During a step, the first leg only generates decelerating forces. The force pattern for the second leg appears much like that produced by a human leg, first decelerating and then accelerating the body. The major accelerating force can be attributed to the third leg, which propels the body from behind. In insects each leg operates differently, but three sum to function as one leg of a biped or two legs of a quadruped. Our most recent discovery on centipedes shows that at fast speeds they also operate as spring-mass systems and have only have three of forty-two legs on the ground at once. Even more surprising is the finding that a wave of legs passing down the body of the centipede can produce the same force pattern as do the individual legs of insects. Sprawled posture animals not only generate large decelerating forces, but perhaps more importantly, they also produce substantial lateral forces in the horizontal plane that have mostly been ignored. We hypothesize that these opposing legs forces can enhance stability.

Morphology appears to be important for self-stabilizing behavior. Wider stances, and therefore greater lateral forces, can result in faster recovery from perturbations. Control can reside in the mechanical design of the system and can be simple. The control algorithms are embedded in the form of the animal itself. Control results from the properties of the parts and their morphological arrangement. Simple, feedforward, predictive planning can be effective for rapid, repetitive, gross behavior if it works in concert with the mechanical system.

Our recent studies on maneuverability reveal the same theme apparent in stability. Climbing, turning and negotiating irregular terrain require relatively minor adjustments to the program generating straight-ahead locomotion. Precise foot placement, follow the leader gaits and body attitude control may not be required for phenomenal performance. Exceptionally rapid and accurate neural feedback can be replaced by a smart mechanical system.

Examining the diversity of animals in nature enables discovery of general principles that can be used to inspire the design of biomorphic explorers capable of in-situ sensing and local sample analysis and acquisition on other planets.

NASA JPL Workshop

POLY-PEDAL LAB
PERFORMANCE ENERGETICS DYNAMICS ANIMAL LOCOMOTION
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Inspiration from Nature toward the Design of Surface-roving Biomorphic Explorers

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Diversity Enables Discovery

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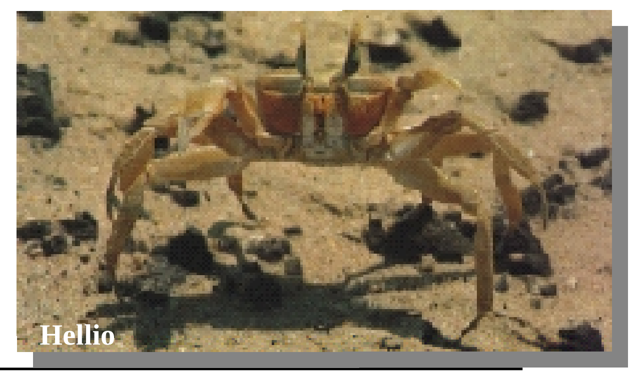
Natural Technologies Offer Splendid Solutions



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Specifications

Small

Rapid

Stable

Simple Control

Maneuverable on Any Surface

Robust

NASA JPL

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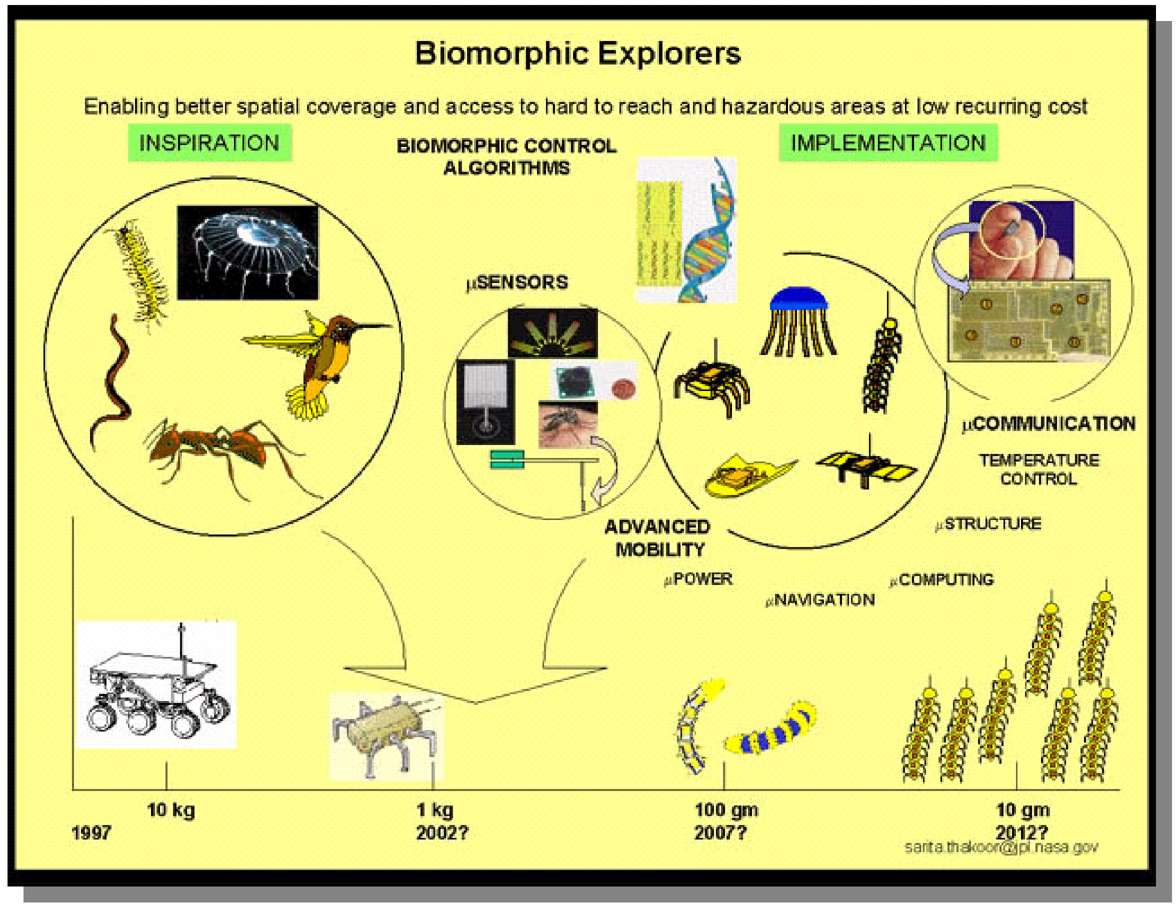
Use Biological Inspiration in the Design of Biomorphic Explorers



Neuro-mechanical Model

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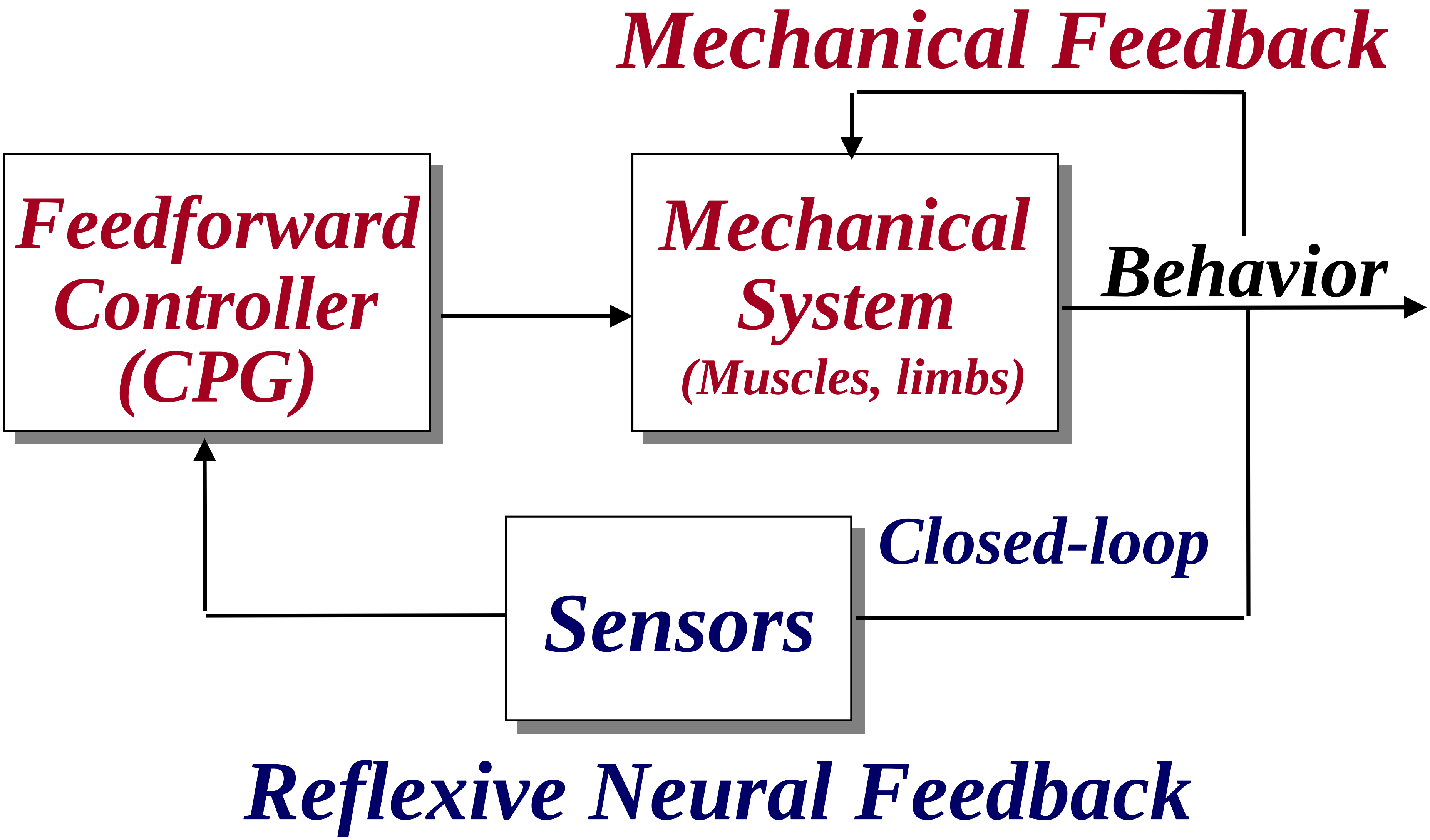
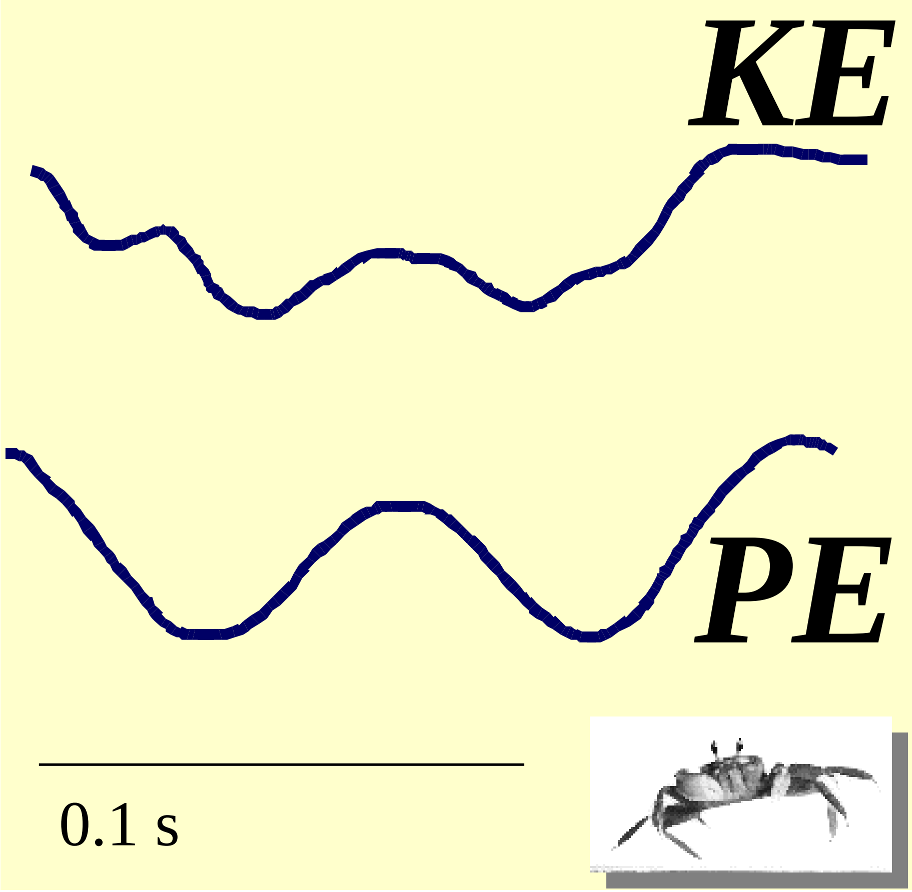
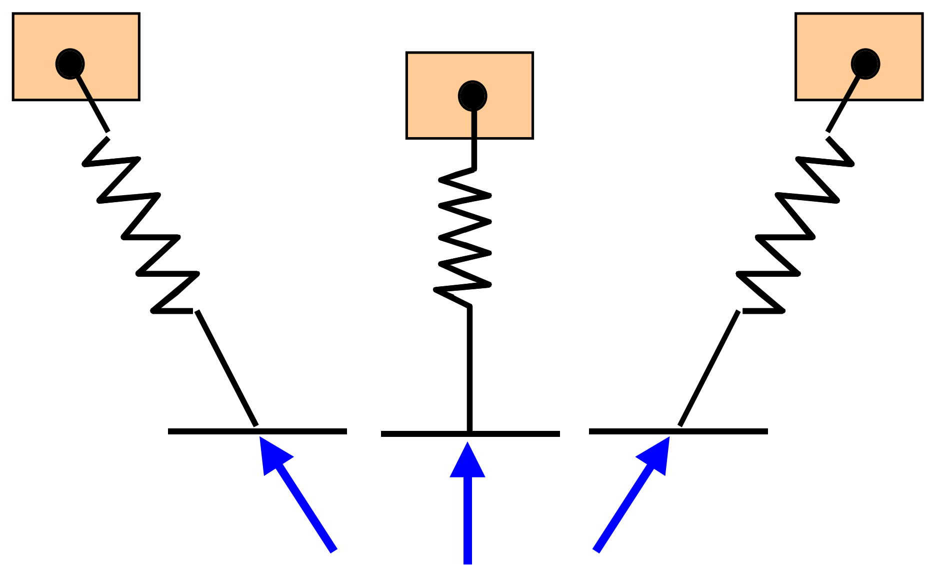


Running

Mechanical Energy

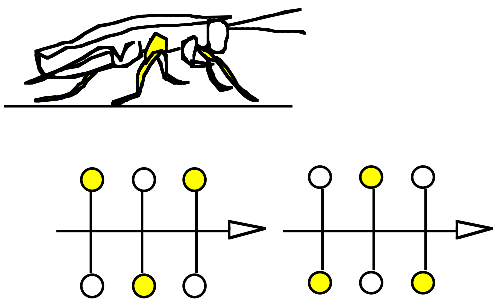


Spring-Mass Pogo Stick



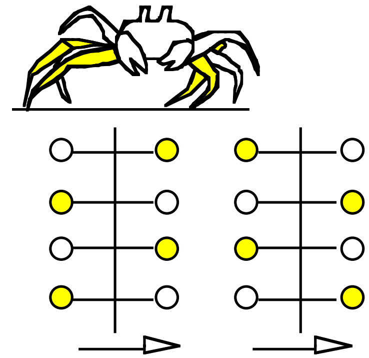
Spring-Mass Systems

SIX-Legged

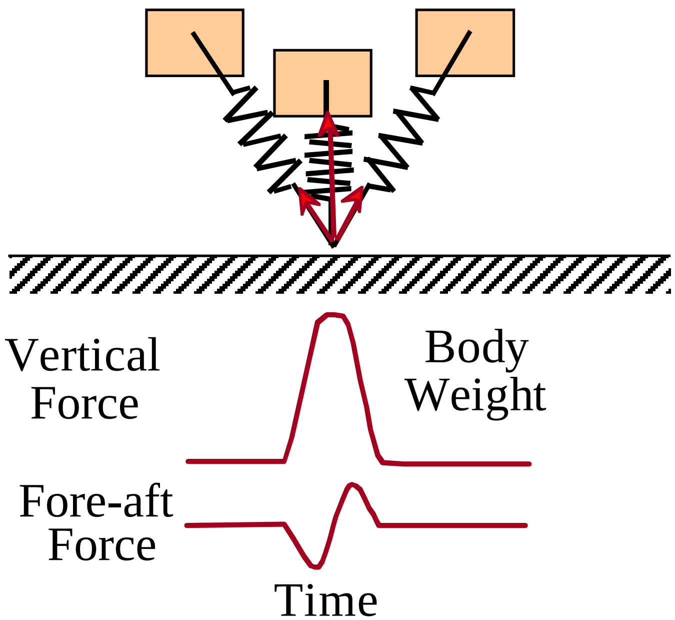


Cockroach

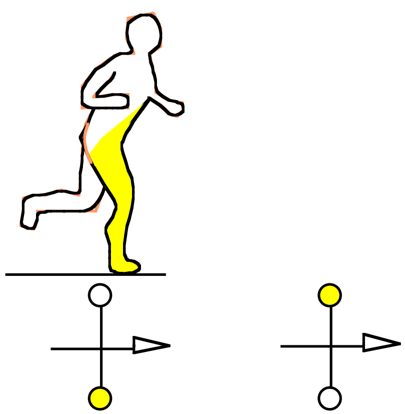
EIGHT- Legged



Crab

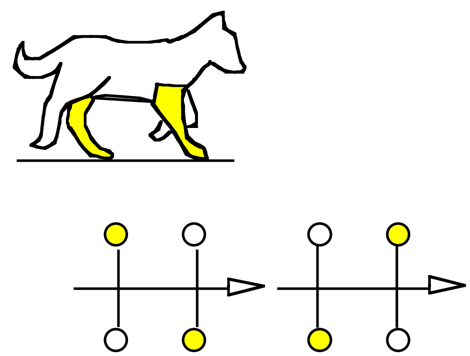


TWO-Legged



Human

FOUR- Legged



Dog

(Full 1989)

Leg Stiffness

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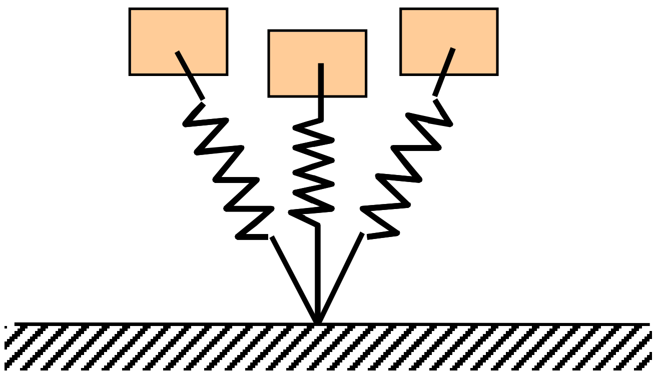
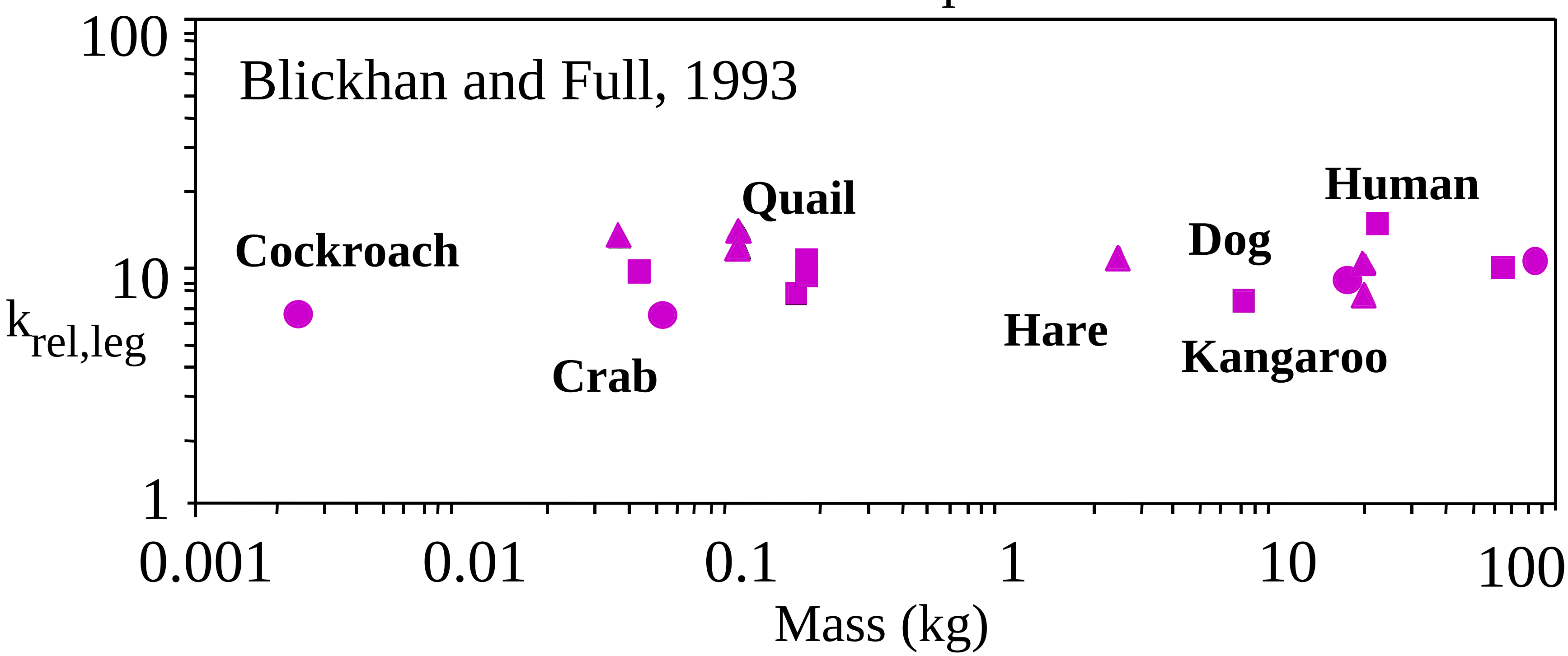


$$k_{rel} = \frac{\frac{F}{mg}}{\frac{d\,l}{l}}$$

TROTTERS ●
RUNNERS ■
HOPPERS ▲



Question

Many Morphologies Permitted!

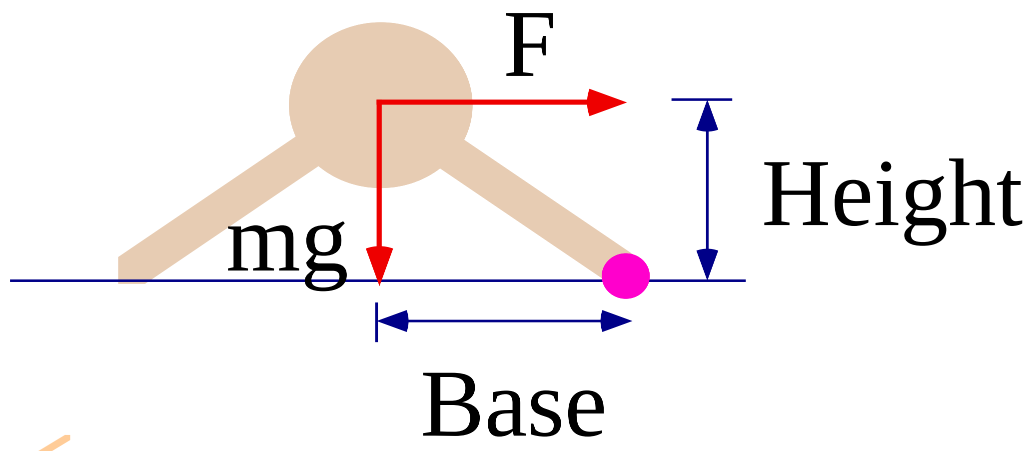
What are the advantages and disadvantages of many legs and a sprawled posture?

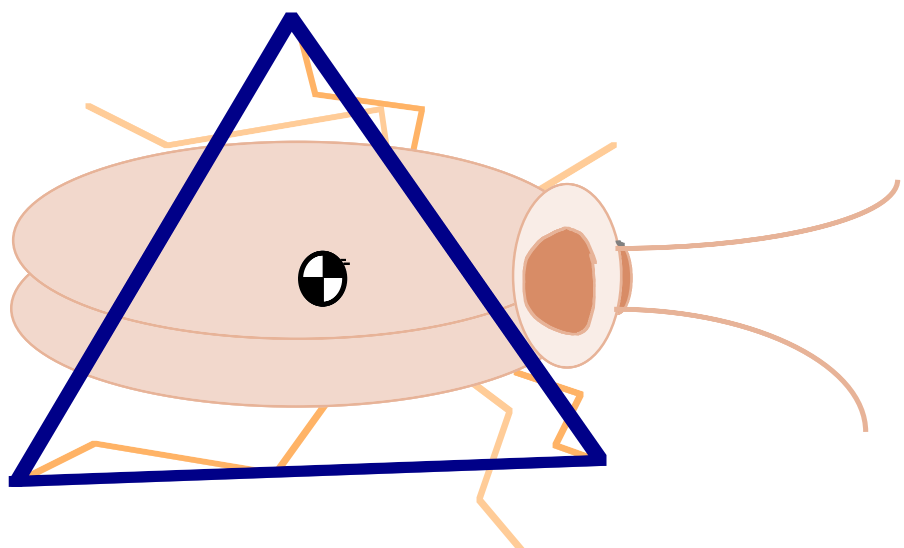
Outline

1. Stability
2. Maneuverability
3. Role of musculo-skeletal units
4. Biological Inspiration

Static Stability

$$F \; \alpha \; \frac{\text{Base}}{\text{Height}} \; mg$$





Leg Number

Posture

Variation in Posture

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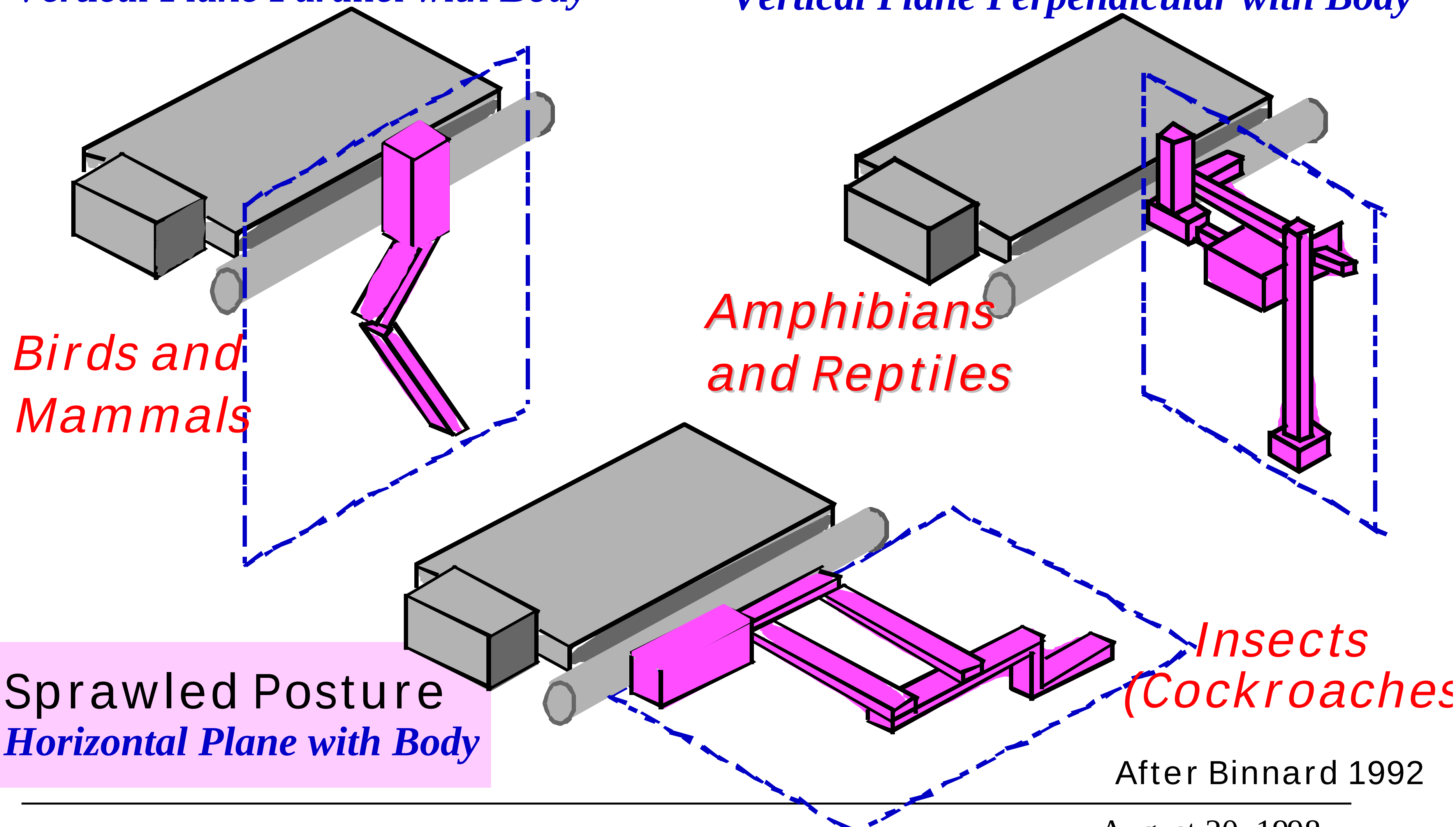
Upright Posture
Vertical Plane Parallel with Body

Sprawled Posture
Vertical Plane Perpendicular with Body



Sprawled Posture
Horizontal Plane with Body

After Binnard 1992

Contention

Stability Important

for many legged, sprawled posture runners

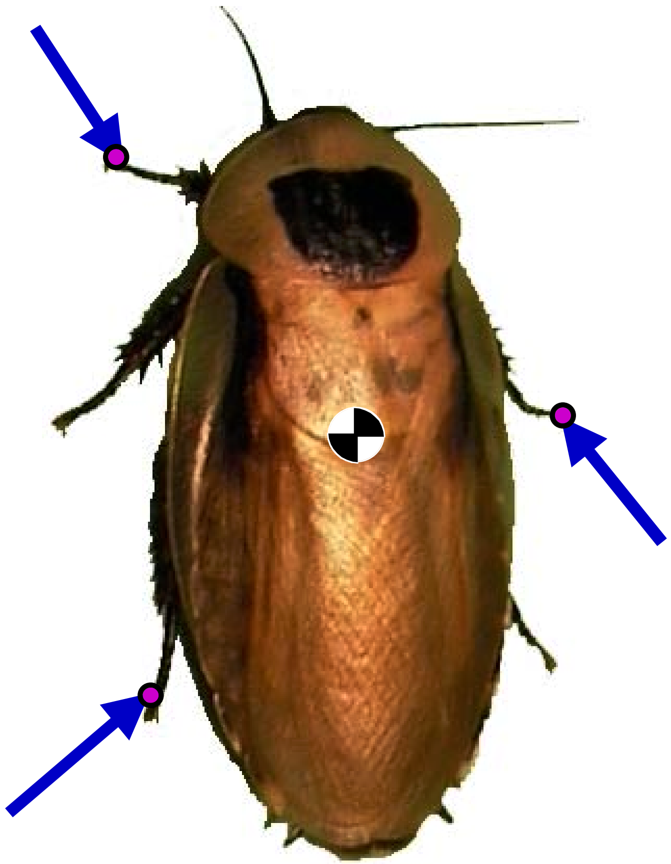
But in the

Horizontal Plane

Force Closure

Differential leg orientation and function advantageous.

Legs positioned all around the center of mass can produce **self-stabilizing** or balancing forces.



Feedforward Model

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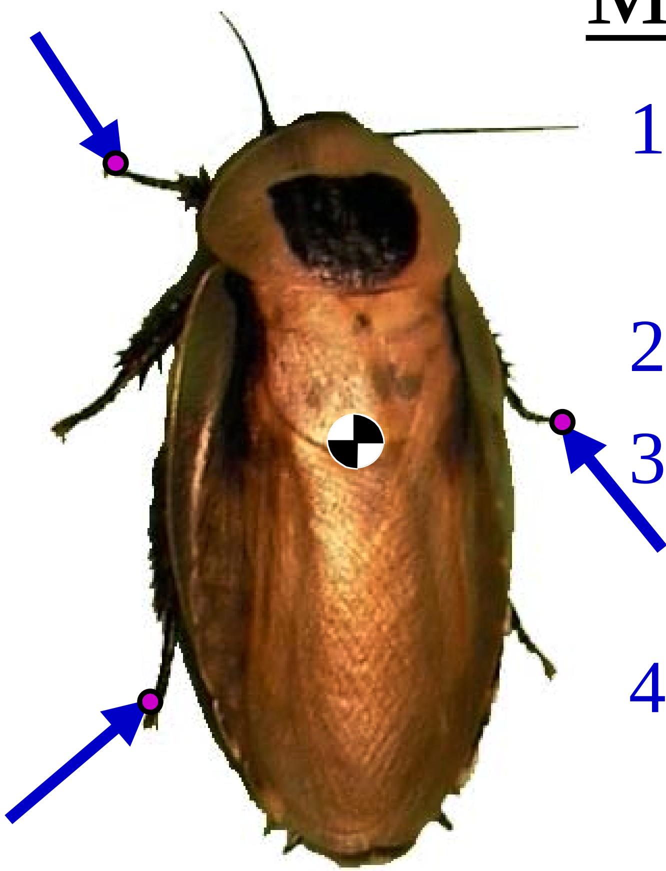
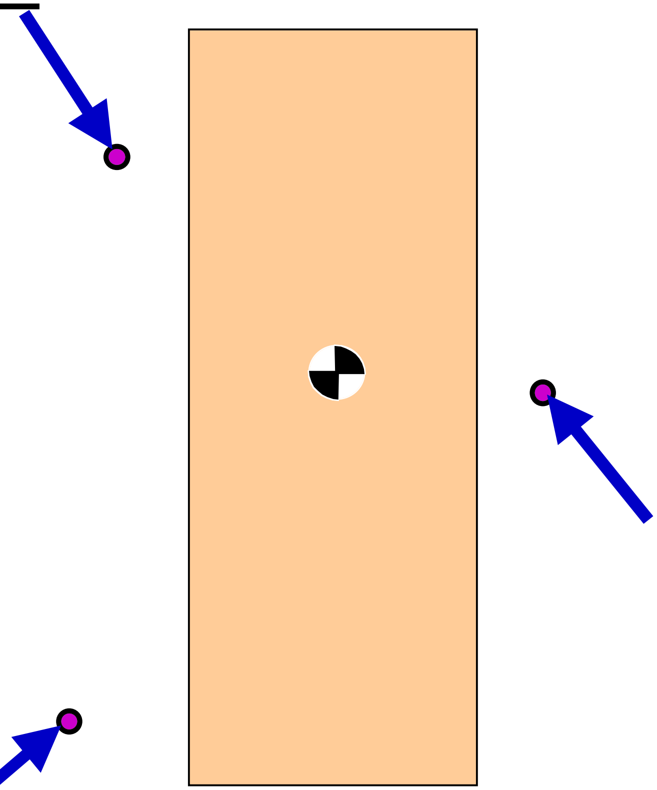
Horizontal Plane



Animal

Measured Inputs

1. Body mass
   and inertia
2. Frequency
3. Foot position
   - initial
4. Leg forces
   - magnitude
   - pattern



Model

Kubow and Full, 1999

Recovery from Perturbation

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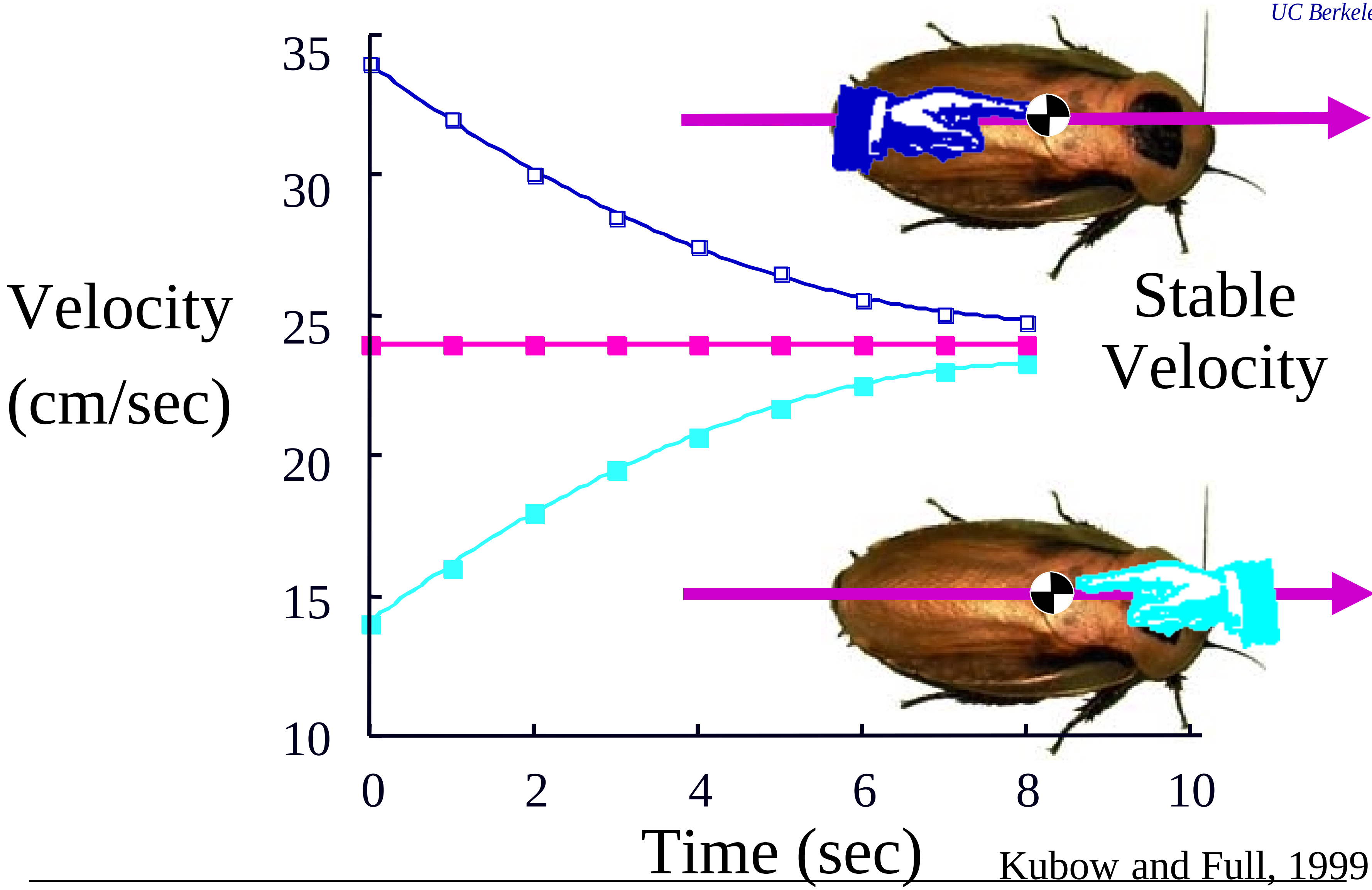

Kubow and Full, 1999

Self-stabilization

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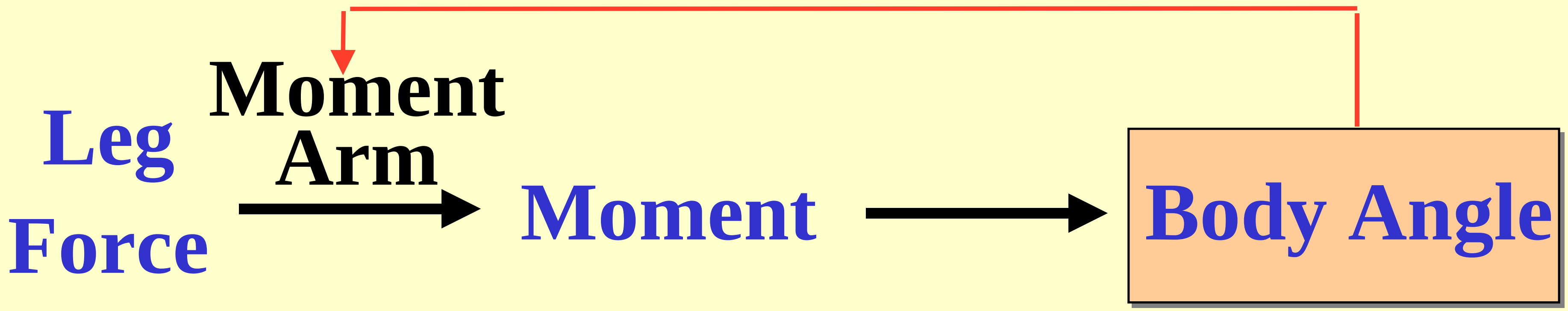
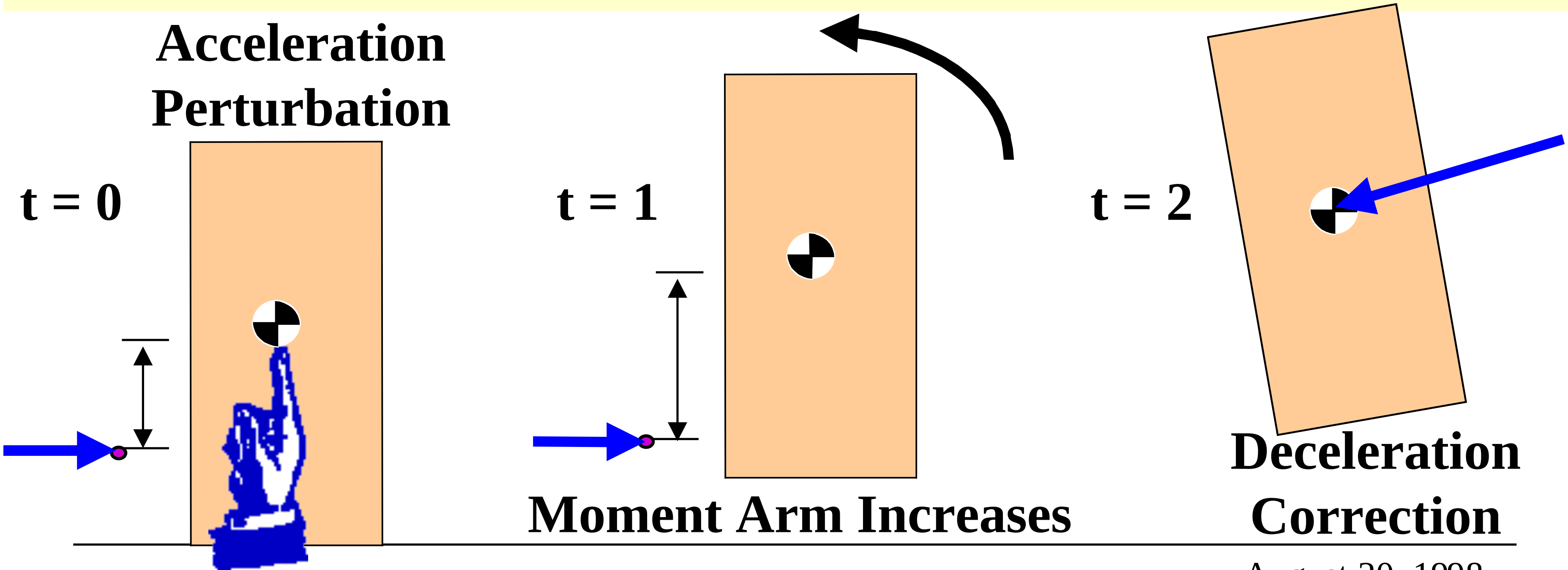
Feedback Through Moment Arm Changes





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PolyPEDAL Control

Control algorithms embedded in the form of animal itself.

Control results from properties of parts and their morphology.

Musculoskeletal units, leg segments and legs do computations on their own.

Outline

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1. Stability

★ 2. Maneuverability

3. Role of musculo-skeletal units

4. Biological Inspiration

3D Dynamic Model

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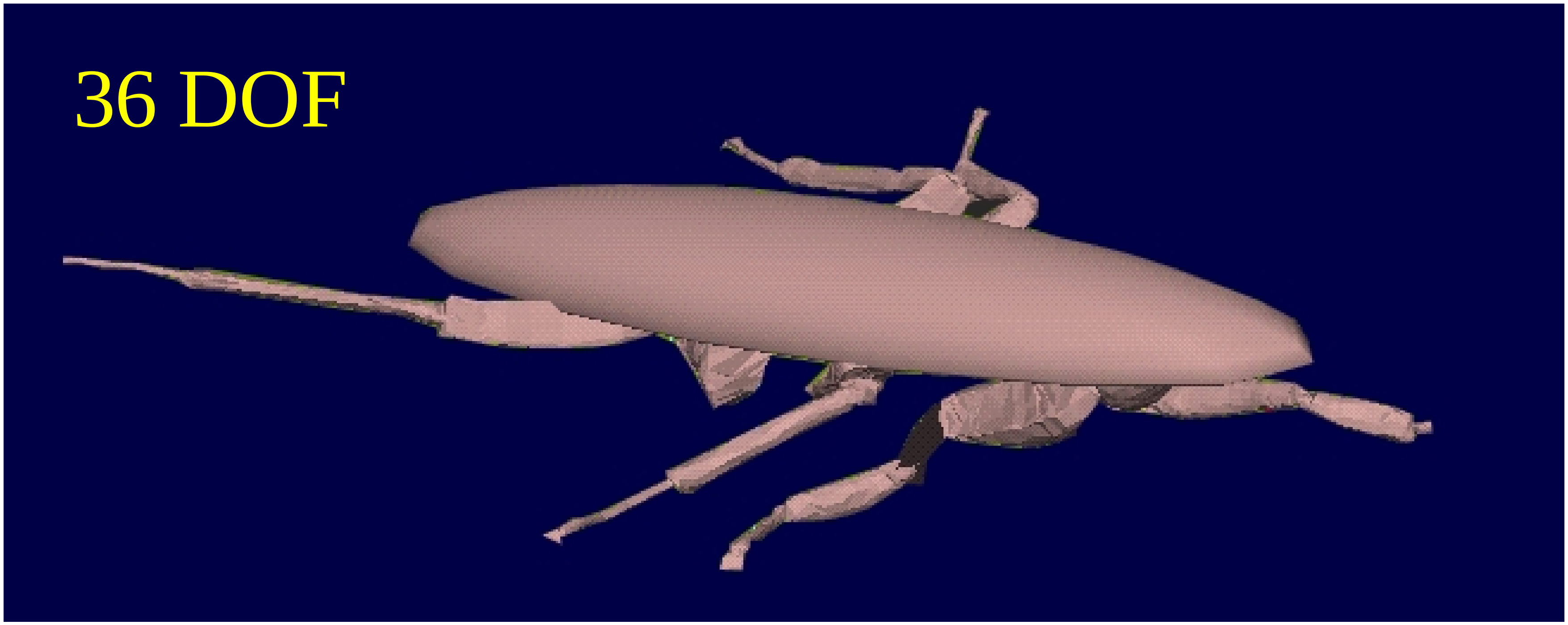

Springs and Dampers at Each Joint

Raibert - Boston Dynamics Inc.

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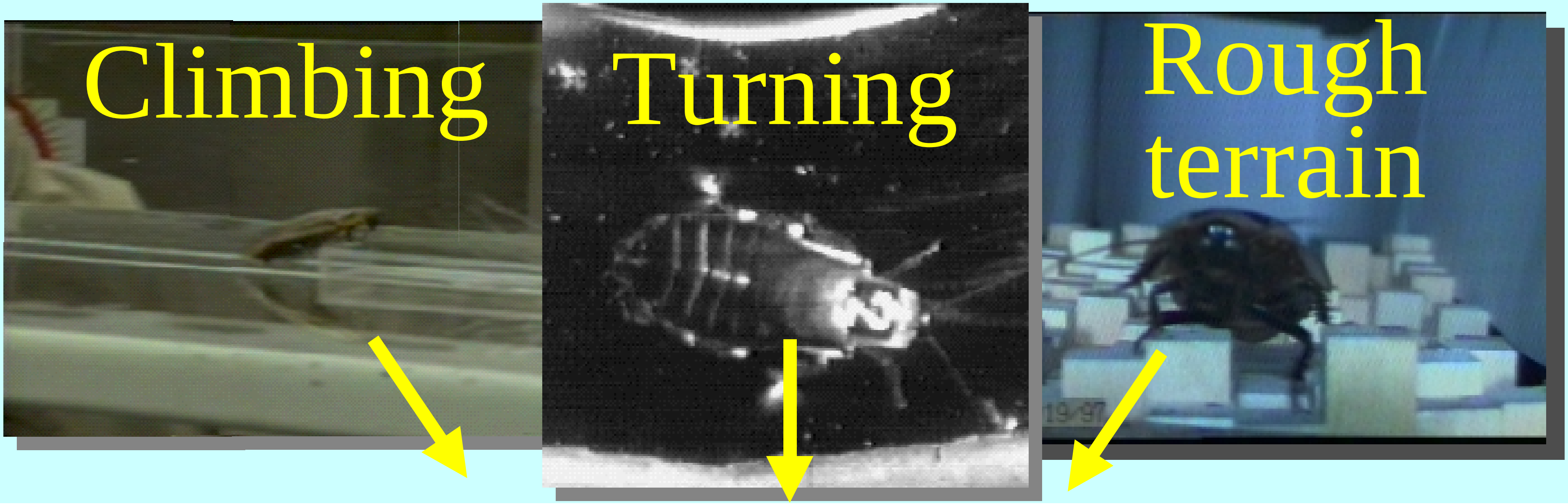
PolyPEDAL Control



Rely on feedforward program

Reduced Reliance	Precise foot placement FTL gait Tactile sensory feedback

Maneuvers Require Minor Alterations of Straight-ahead Running

Outline

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2. Maneuverability

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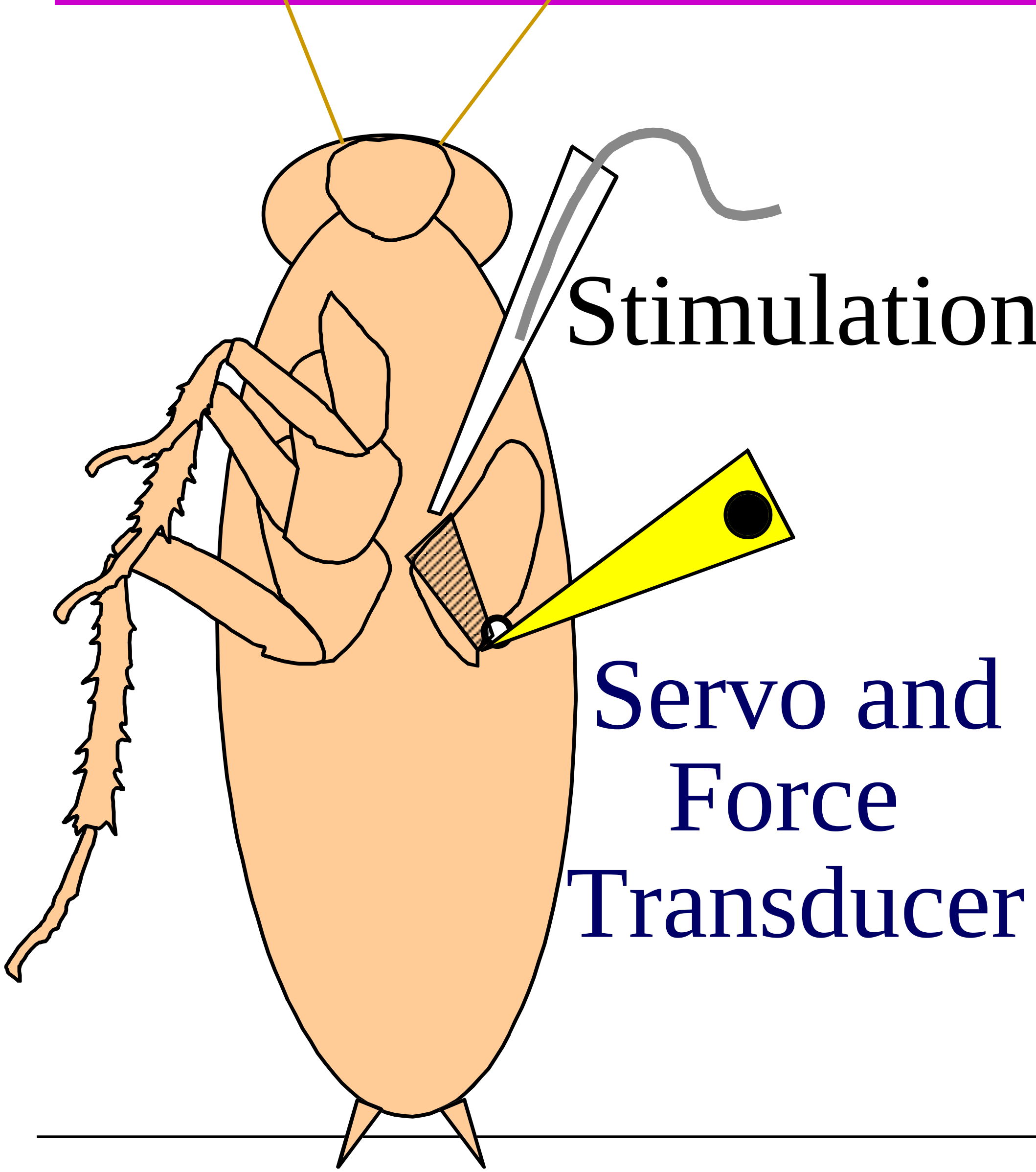
Muscle Lever



Control

Stimulation
- pattern
- magnitude
- phase

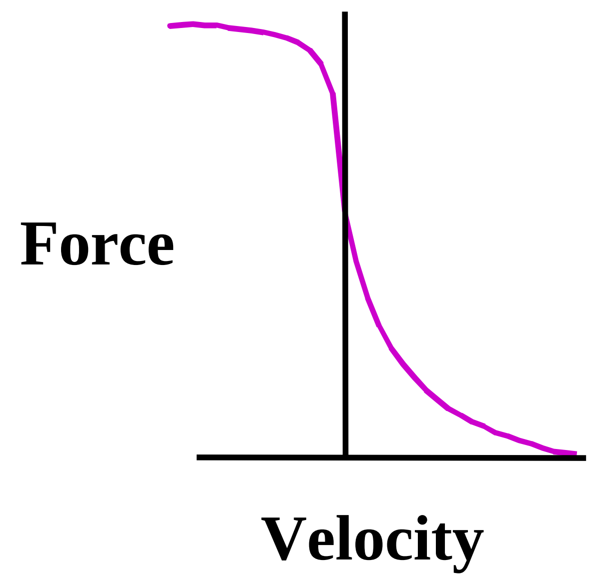
Strain
- pattern
- magnitude

Frequency

Musculo-skeletal Model

Preflexes

Intrinsic musculo-skeletal properties



Brown and Loeb, 1996

Outline

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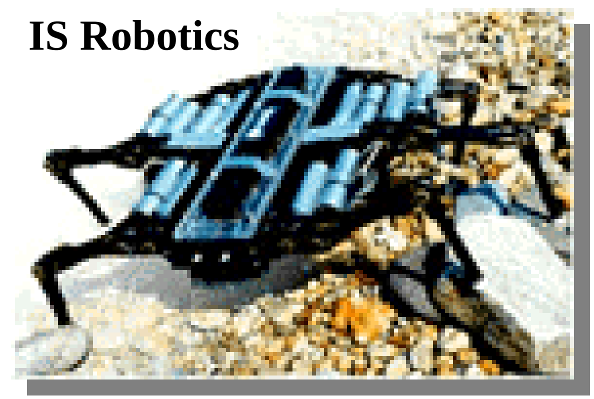
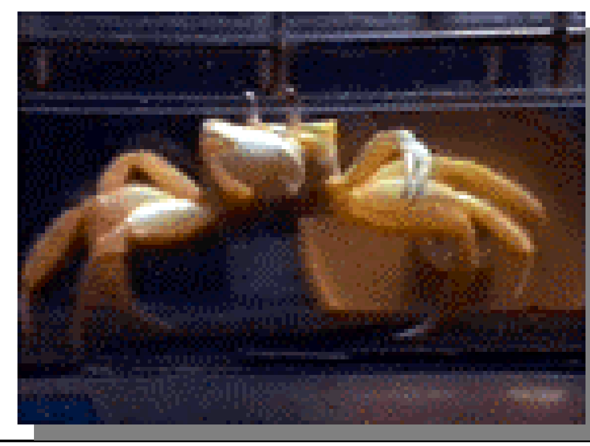
Biological Inspiration

General Principles Anchored in Organismal Design Inspires the Design of New Robots

Faster, Cheaper, Many

Used Reduced Gravity Model to Explain Underwater Locomotion





Burrowing

Biological Inspiration not limited to mobility platforms.

Exceptional diggers and burrows.

Hexapeds

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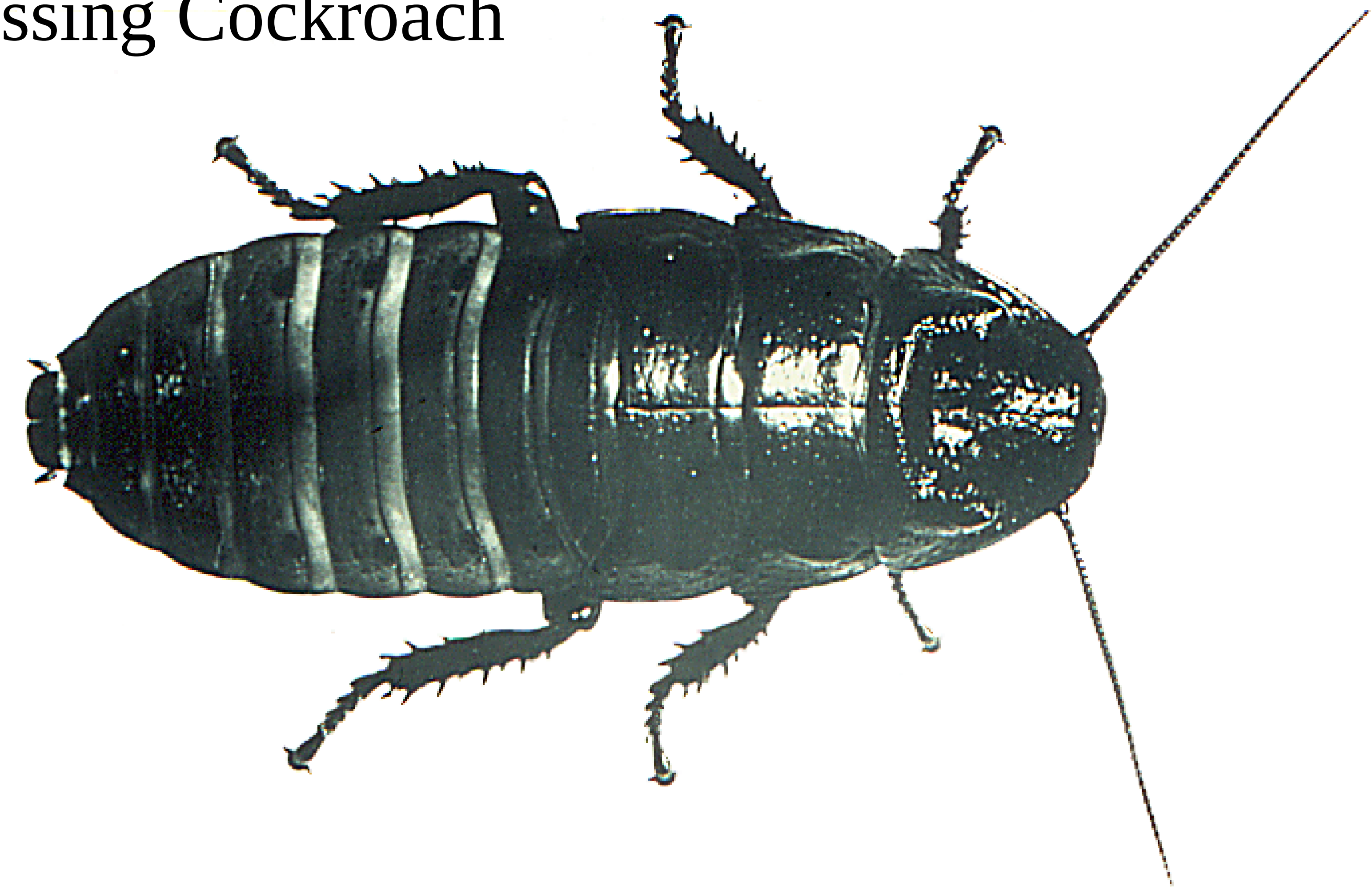
Hissing Cockroach



Millipede

Lessons

1. **Stability in the Mechanical System**
   - **work with coupled dynamics**

2. **Maneuverability a Minor Variation**

3. **Musculo-skeletal units diverse**
   - **assist in local control**

4. **Biological Inspiration**
   - **principle transfer not copying**